

Thermoelectric Devices and Diamond Films for Temperature Control of High Density Electronic Circuits

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ABSTRACT

The increased speeds of integrated circuits is accompanied by increased power levels and the need to package the IC chips very close together. Combined, these spell very high power densities and severe thermal problems at the package level. Conventional packaging materials have difficulty dealing with these thermal management problems. However, it is possible to combine both active and passive cooling by using thin film bismuth-telluride thermoelectric coolers (microcoolers) and diamond substrates for the temperature control of these high density electronic circuits. The highest power components would be mounted directly onto thin film thermoelectric elements, which would maintain the temperature of these components from a few degrees to tens of degrees below that of the diamond substrate. This allows these components to operate within their required temperature range, effectively manage temperature spikes and junction temperatures, and increase clockspeed. To optimize the design of the thermoelectric cooler and operate at maximum efficiency, diamond films acting as thermal lenses would also be used to spread the heat from the small power device to the larger coolers. In those instances where the devices are all operating above ambient temperature, high thermal conductivity diamond films alone are sufficient to cool these devices, by effectively conducting the heat throughout the board.

INTRODUCTION

The need for increased speeds of integrated circuits is accompanied by increased power levels and the need to package IC chips very close together. Combined, these spell very high power densities and severe thermal problems at the package level. Conventional packaging materials have difficulty dealing with these thermal management problems. However, it may be possible to use a combination of active and passive cooling techniques (thermoelectric coolers and very good thermal conductors such as diamond films) for the temperature control of these high density electronic circuits.

We have modelled the case of a typical power amplifier (PA), operating at temperatures substantially above ambient, used in spacecraft applications to determine the advantages and

drawbacks of using either thermoelectric coolers or diamond films or both. The results are not surprising but suggest several possible applications for thermoelectric coolers.

RESULTS AND DISCUSSION

Active and passive cooling at temperatures above ambient:

A 5 watt solid state power amplifier (f 'A) was used, as a current relevant spacecraft application example, to determine the applicability of thermoelectric coolers and diamonds films relative to temperature control. The PA is 5.4 mm by 3 mm on a 0.10 mm thick gallium-arsenide substrate. The device operates in such a way that 8 watts of thermal power must be conducted away from the PA and that the peak allowable operating temperature of the PA is 110°C. The power producing portion of the PA only occupies about 5% of the total PA area. A simple 2 dimensional finite difference thermal model [1] was used to determine the peak temperature of the PA assuming a uniform temperature on the back surface of the PA. The result was that the peak temperature of the power producing portion of the PA will be about 25°C above the back surface of the PA. The thermoelectric cooler could be used to counteract this temperature differential across the PA substrate.

It was decided to design a thermoelectric cooler which would compensate for only 10°C of the temperature differential across the PA, in order to achieve a high coefficient of performance (COP). This was done to determine the overall impact of the cooler on a system basis. The theoretical maximum COP which can be obtained with current state of the art material is about 3 to 4, depending upon the average temperature of operation [2]. Standard available thermoelectric coolers utilize bismuth telluride alloys for the active material. The smallest leg size for standard coolers is 0.64 mm by 0.64 mm in cross section. If a cooler, with this size legs, is put over the entire back surface of the PA, only a total of 16 couples will fit. With this leg size, it will be very difficult to get 8 watts of cooling. This could be obtained only with extremely short legs, 0.2 millimeters or less. It was assumed that each electrode and their associated contact has an electrical contact resistance of $2.5 \mu\Omega\text{-cm}^2$. With this leg length, the electrode and contact resistances become a very significant portion of the total resistance and should be modeled more accurately. At this short leg length, it was estimated that the cooler would require nearly 18 watts of electric power in order to generate 8 watts of cooling power- with a 10°C temperature differential. This corresponds to a coefficient of performance of only 0.44.

The major drawback with the microcoolers required for cooling of the PA is the low coefficient of performance. This very poor performance, about 9 times lower than the maximum theoretical COP, is due to the far from optimum values for the length and cross-section of the thermoelectric legs imposed by this design. An additional problem with this cooler configuration is the high current and low voltage required. It requires 9 amps at about 2 volts. The 2 volts is below any voltage typically available on the spacecraft,

This results in two problems: 1) high electrical power requirements, and 2) poor overall cooling of the electronic device to be cooled. The high electrical power requirement, means that more power will be required for the cooler than for the device itself. in order to be

practical for spacecraft applications, a microcooler would have to have a coefficient of performance greater than 5. The second problem is even more troublesome. Because of the low coefficient of performance, now the heat rejection of the PA has increased from 8 watts to 26 watts, as a result of the 18 watts of power needed for the cooler. Since currently there is an even larger temperature gradient going from the back side of the chip to its radiator than there is across the substrate of the chip, this increase in heat rejection will actually increase the temperature of the PA. In order to reduce the temperature of the PA by 10°C the heat rejection has to be more than tripled. This will increase the temperature differential along the board on which the PA is mounted, as well as the temperature differential from the board to the housing. This will result in an increase, rather than a decrease in the PA temperature, defeating the purpose for which the cooler was used.

For such an electronic device operating at a temperature above ambient, the solution is thus to improve the thermal conductivity of the board on which the high power components are mounted, rather than use a thermoelectric cooler (thermoelectric coolers should only pump heat from cold to hot). The use of diamond films will accomplish this. Diamond has a very high thermal conductivity (about $2400 \text{ Wm}^{-1}\text{K}^{-1}$ at room temperature) and is an insulator, making it ideal for this purpose [3]. The use of diamond films will reduce the temperature differential along the board where the chips are mounted. This is typically greater than the temperature differential across the substrate of any chip in the case of the conventional board materials such as alumina or Kovar. Typically, the center of a diamond substrate will not be more than a few degrees higher in temperature than the temperature of the housing (external heat sink of about 50°C in spacecraft). Hence in the case of a diamond board, the power producing part of the PA would now be at about 25°C above the temperature of the back surface of the external housing (compared to at least 20 to 30°C higher in the case of an aluminum board). Thus the use of diamond films (with the highest thermal conductivity known) will set the limit of passive cooling techniques for circuits. Currently, the price of diamond films is still too high for them to be generally used and all the metallization, bonding and contacting problems have not been solved yet. However, diamond films offer a tremendous improvement in passive temperature control of electronic circuits over that of the current materials used,

Thermoelectric Cooler Application

However, two situations where thermoelectric coolers operating at temperatures above ambient would serve a useful purpose were determined. The first of these is where a high power component operates under very transient conditions. If the device only requires high power levels for short periods of time, then a thermoelectric cooler could be useful. It would only be operated when the device needing cooling is operated. It would thus reduce the temperature spikes by more effectively using the heat capacity of the board on which the cooler is mounted.

The second situation where a thermoelectric cooler would be beneficial is if one of two components must be kept at a much lower temperature than all the rest of the electrical components. This could occur with the use of silicon carbide for the majority of components, while a couple of silicon or gallium arsenide components are still being used. Then a

thermoelectric cooler could be used just for the low temperature components, allowing the board to run at the higher temperature of the other components.

A third and most interesting situation arises when a device is kept below the ambient board temperature so that substantial increases in performance, clock speed and reliability can be achieved. As an example, a diamond substrate would be at the ambient temperature of 20°C while the device would be operated at -20°C by using a thermoelectric cooler. There is of course a trade off between increase performance of the device and cost of the thermoelectric cooling unit. Each case would thus have to be considered on its own merits by considering the measurable improvement in clockspeed and performance, the increase in mean time between failures, the temperature difference through which the heat needs to be pumped and the cost of the cooling device.

Figure 1 shows the large increase in failure rate (normalized to the room temperature rate value) with increasing temperature. This Arrhenius plot is only for illustration purpose as different activation energy values can be obtained for various electronic chips [4, 5]. It is very likely that there are already electronic devices where operation below ambient would be beneficial and would make sense cost wise. It appears extremely likely that in the near future a larger number of devices will have to operate at lower and lower temperatures because of the anticipated substantial increase in power output and the need to increase clockspeed even further.

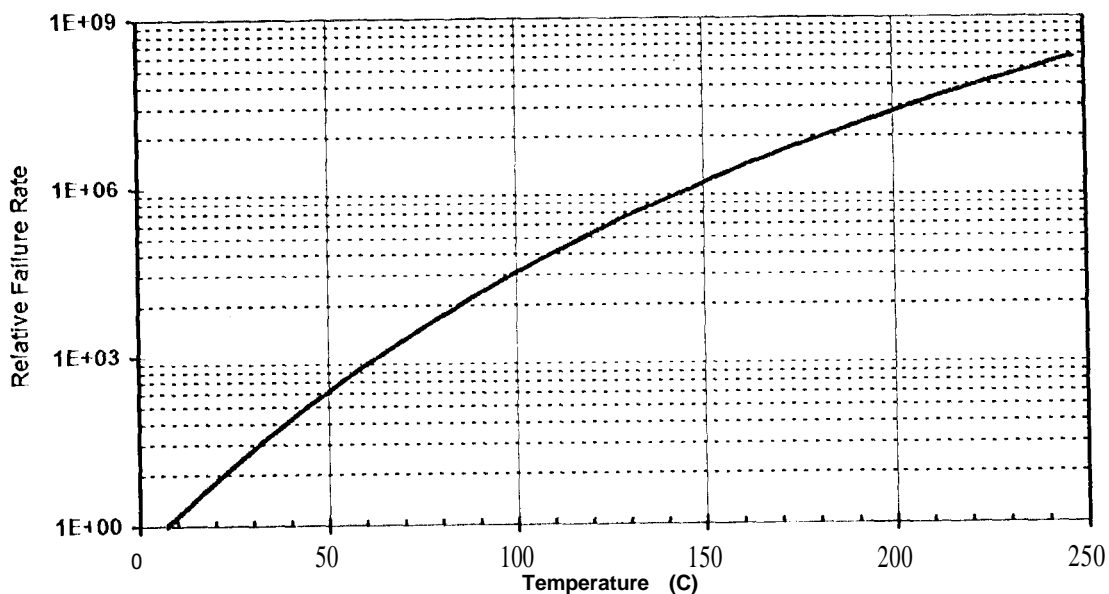


Figure 1: Relative failure rate normalized to the room temperature rate value as a function of temperature (activation energy is 1 eV).

Since the COP of a thermoelectric cooler increases nearly exponentially with decreasing temperature difference, it is critical that the cooler be as close to the power-producing portion of the device as possible. This would mean attaching the thermoelectric cooler directly to the die. In addition, using a diamond film substrate as the heat sink would keep the temperature difference at a minimum by both conducting efficiently the heat and power added to the cooler away without hardly increasing the heat sink temperature. This combination of active

and passive cooling allows a device to be kept below ambient with the smallest temperature difference. A diamond film can also be used between the device and the cooler in the case when the area of the device is too small to accommodate the cold side area of the thermoelectric cooler needed to pump the heat produced through the required temperature difference. The diamond film would thus act as a "thermal lens" by effectively spreading the heat over a larger area with only a very small temperature drop across the film. If diamond does not work out because of bonding problems, then another high thermal conductivity material could be used (such as BN or AlN).

An improved thermoelectric material with a ZT greater than for state of the art Bi_2Te_3 -based alloys would allow the device to be cooled at lower temperatures for the same power input into the cooler or would require less electrical power to operate the same temperature difference. Compared to current state of the art performance, a cooler operating at maximum COP with an average ZT of 2 would reduce the electrical input power needed by about 50% for a ΔT of 10°C to by more than 70% for a ΔT of 50°C (See Figure 2). An improved thermoelectric material is hence very desirable for spacecraft applications because of the limited power available.

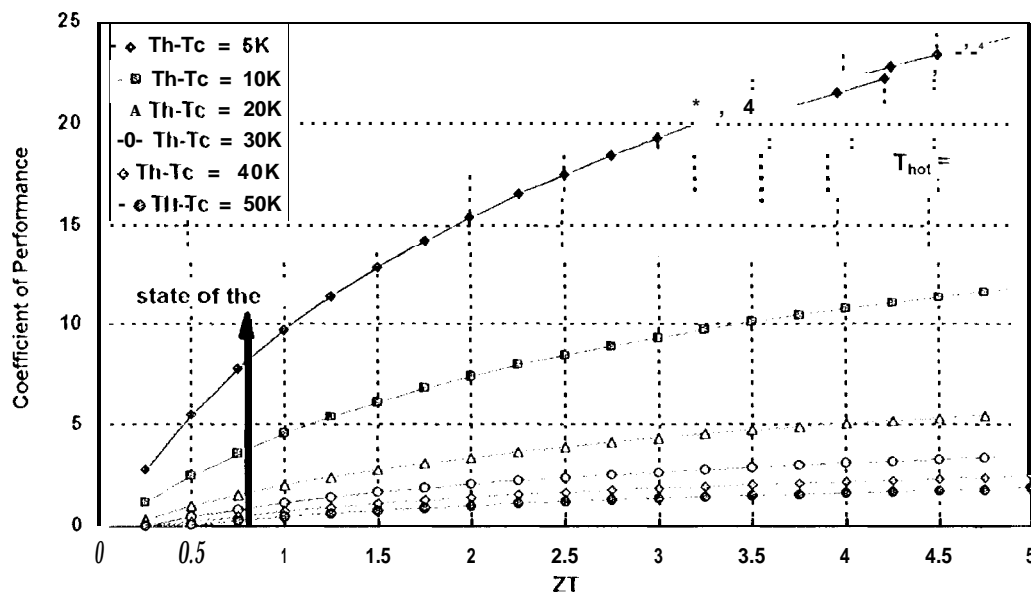


Figure 2: Maximum coefficient of performance ((XII')) as a function of the average ZT value and for different temperature differences ΔT .

CONCLUSION

Thermoelectric coolers are not generally useful for the temperature control of high density electronic circuits as our example clearly showed. Passive cooling with high thermal conductivity diamond films will be much more useful for the cooling of circuits above room temperature. However, there are three situations where active cooling with thermoelectric coolers would serve a useful purpose: a component only uses high power for very short periods of time, or a single component must operate at much lower temperatures than the rest

of the components in the circuit, or when a device needs to be cooled well below ambient temperature to increase its clock speed. Two areas where development would improve thermoelectric microcoolers are: an improvement in the thermoelectric material and the reduction of the electrical contact resistance. Both of these improvements would increase the coefficient of performance of the cooler making it more beneficial.

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